



# ***Fabrication and Testing of Advanced Thermoelectric Unicouples for Power Generation***

*presented at the*

**21<sup>st</sup> International Conference on Thermoelectrics**

**Long Beach, CA**

**August 2002**

by

**J. Sakamoto, J. Snyder, A. Zoltan., D. Zoltan and T. Caillat**

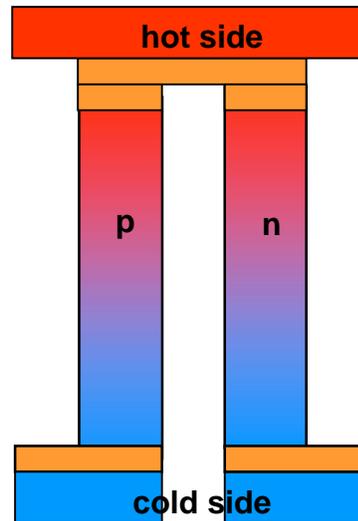
**Jet Propulsion Laboratory/California Institute of Technology**

**Pasadena, CA, USA**

# Program overview

- Engineering and testing
- Unicouple fabrication
- Modeling

- Materials Research
- Develop high ZT materials
- Materials synthesis
- Improve thermal stability and compatibility

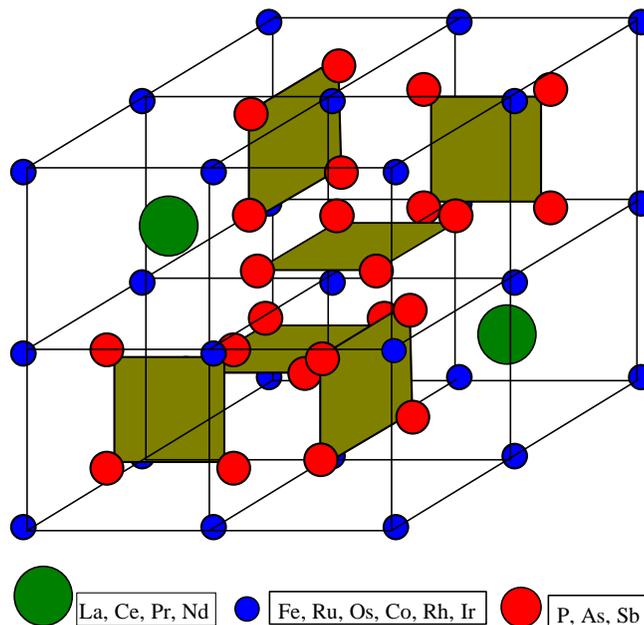


- High-efficiency prototype

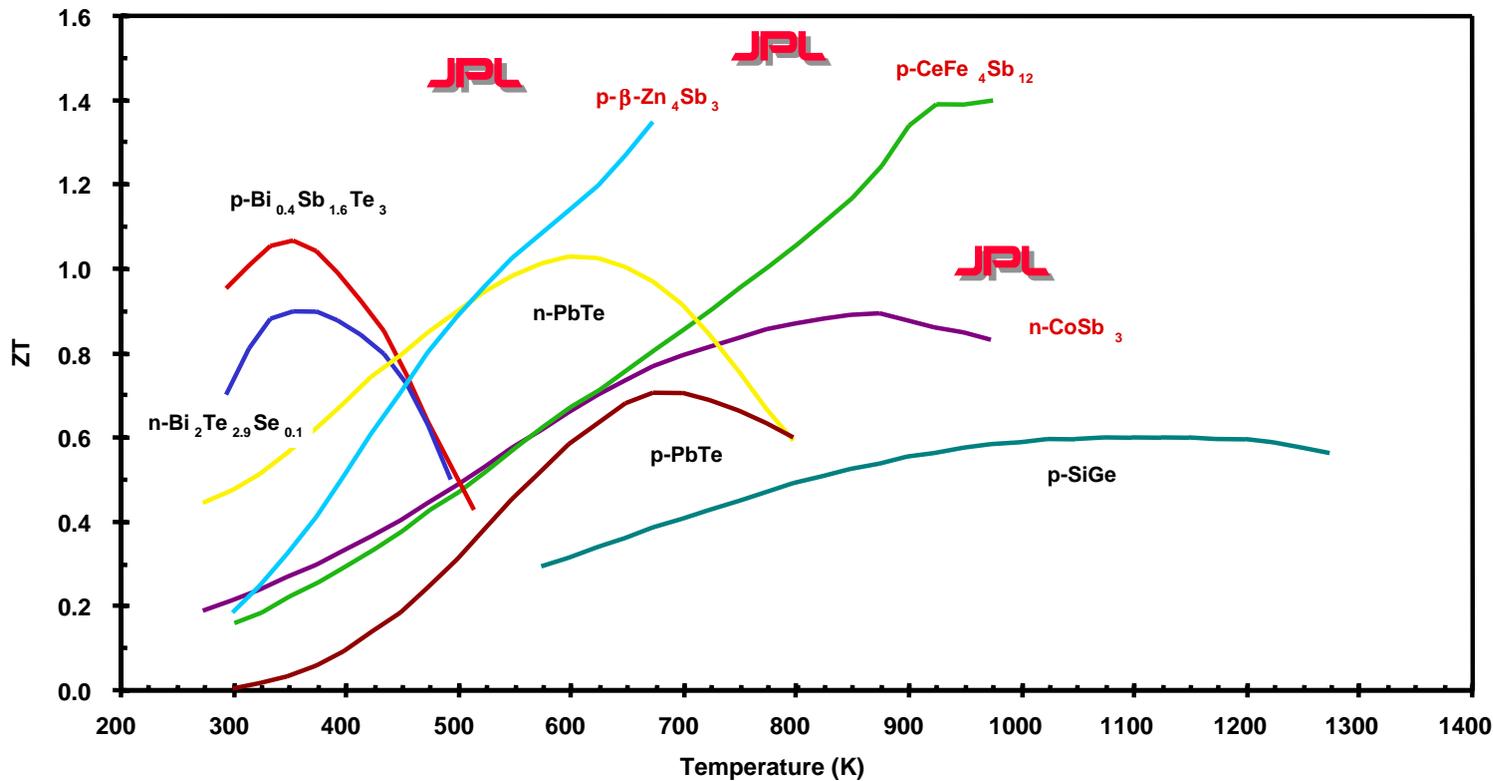
## Advanced Thermoelectrics DARPA & ONR effort at JPL

### ■ Bulk materials

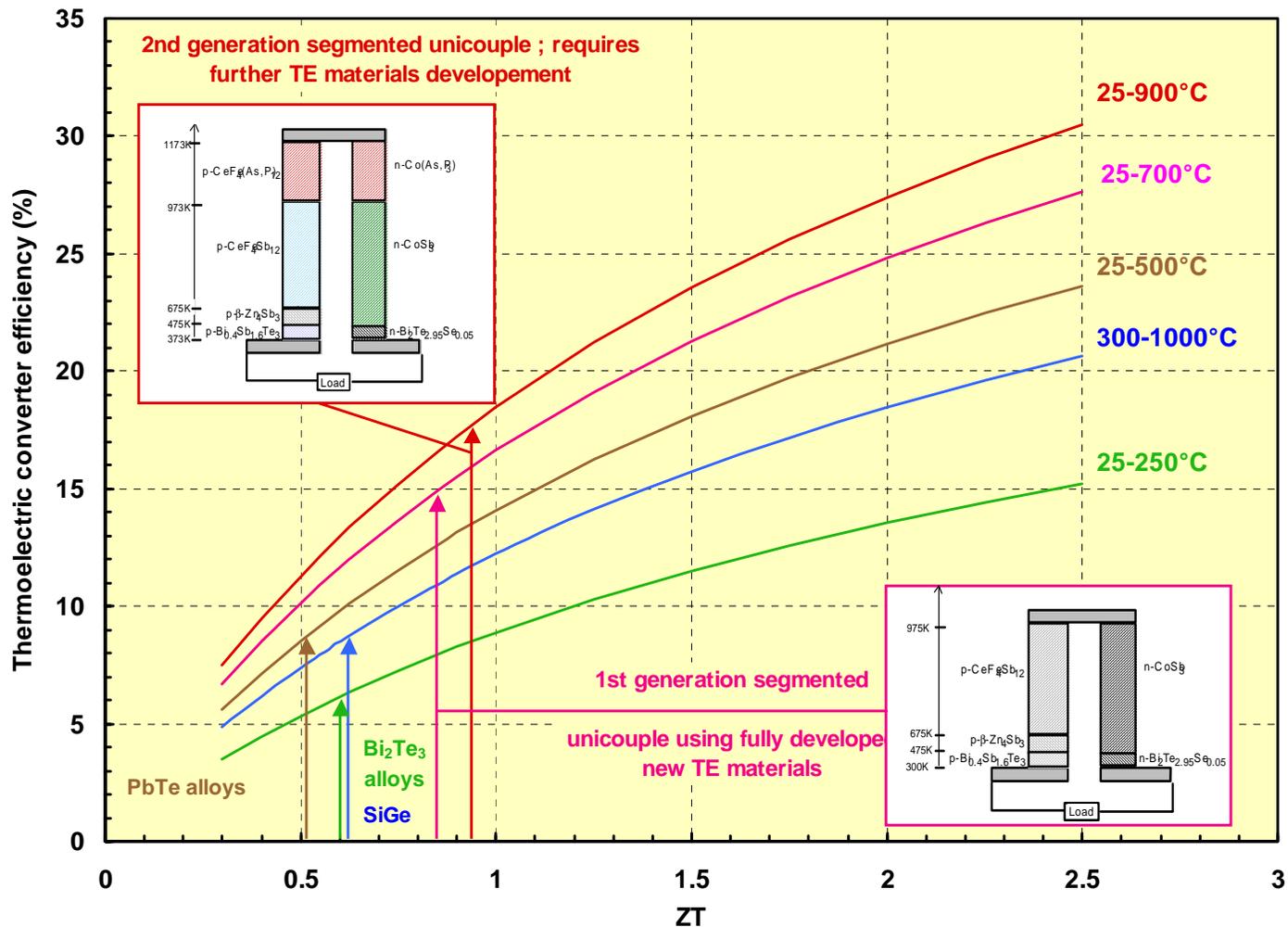
- DARPA “Advanced Thermoelectrics” and ONR “Skutterudites”
  - ◆ Focus on TE materials for cooling and power generation up to 600-700°C
  - ◆ Identification, characterization and optimization of some new, promising materials
  - ◆ Skutterudites



## Best ZT to date on new materials developed at JPL



- Combine best new material (Skutterudite) with the best SOA (BiTe)

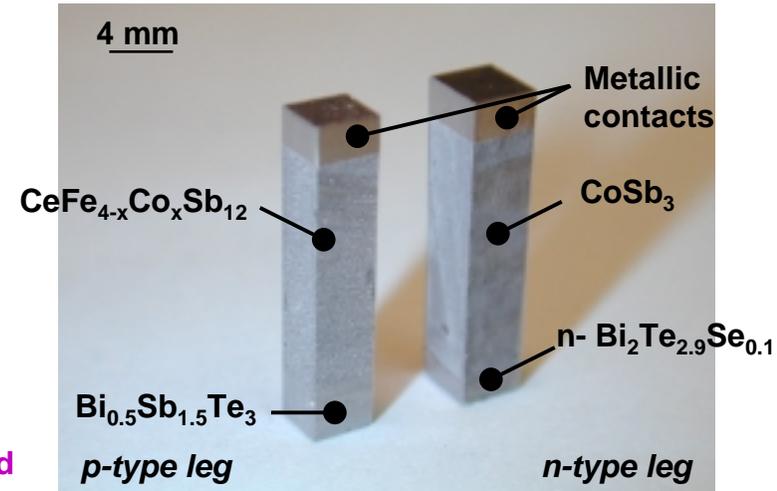


- Projected performance is double SOA technology

# Segmented legs: fabrication and testing

## Segmented leg fabrication

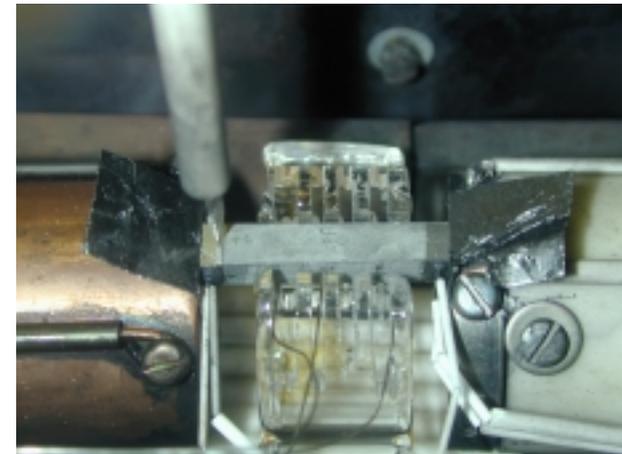
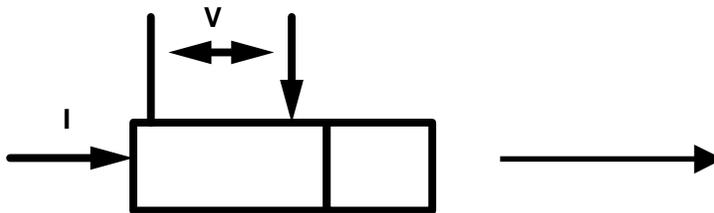
- Uniaxial hot-pressing of powder stacked on top of each other
  - ◆ Temperature optimized  
→ density close to theoretical value
  - ◆ In graphite dies and argon atmosphere
- With metallic foil between segments
  - ◆ Selected to compensate for coefficient of thermal expansion mismatch
  - ◆ Diffusion barrier
  - ◆ Should react chemically with both materials to be bonded
  - ◆ Low electrical resistance bond ( $<10\mu\Omega\text{cm}^2$ )
- Metallic contacts at hot-side



Segmented legs fabricated by uniaxial hot-pressing

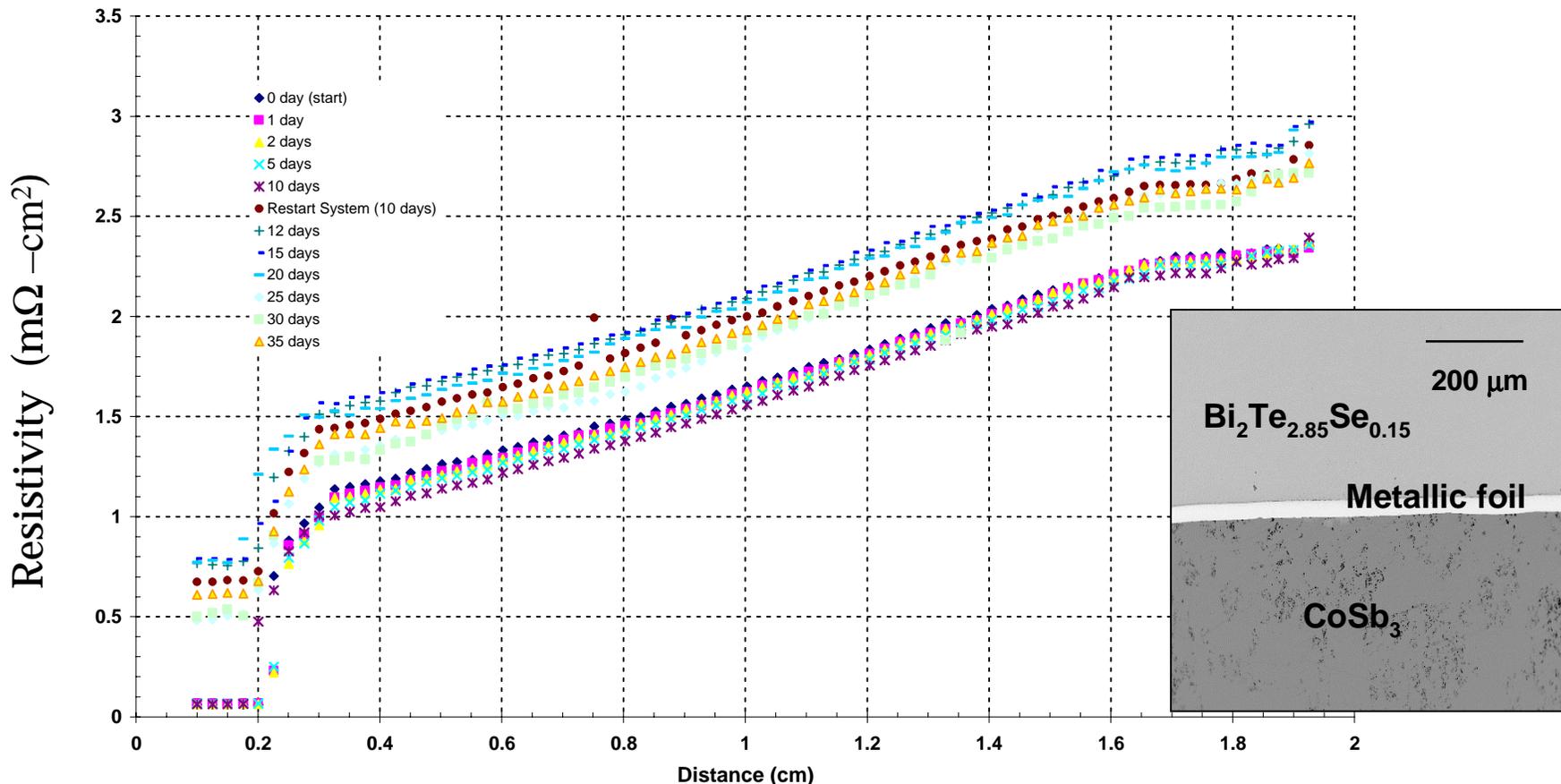
## Bond quality

- Electrical contact resistance measurement
- Microprobe analysis
  - ◆ Diffusion
  - ◆ Chemical reaction and interface layer analysis



# In gradient, electrical contact resistance life tests on $\text{Bi}_2\text{Te}_{2.85}\text{Se}_{0.15}/\text{CoSb}_3$ segmented leg (n-type)

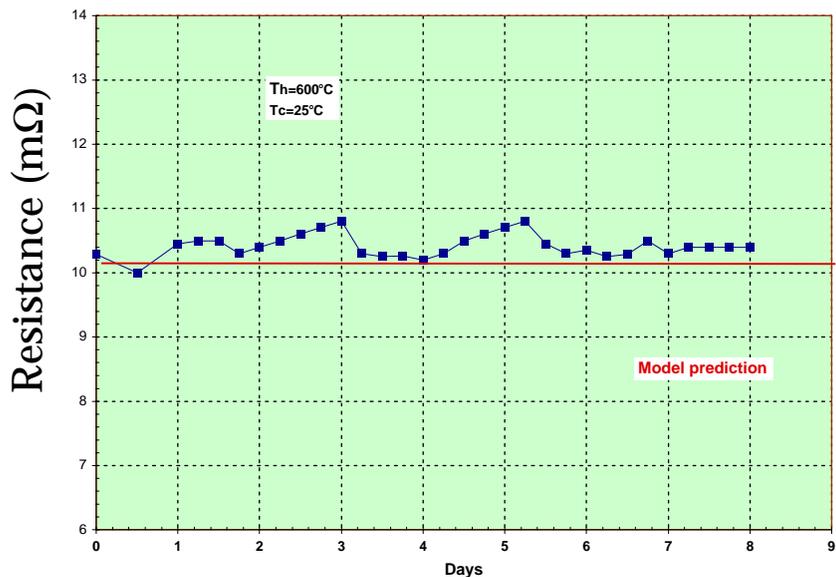
Junction-169 (Resistivity at 600°C vs Time)



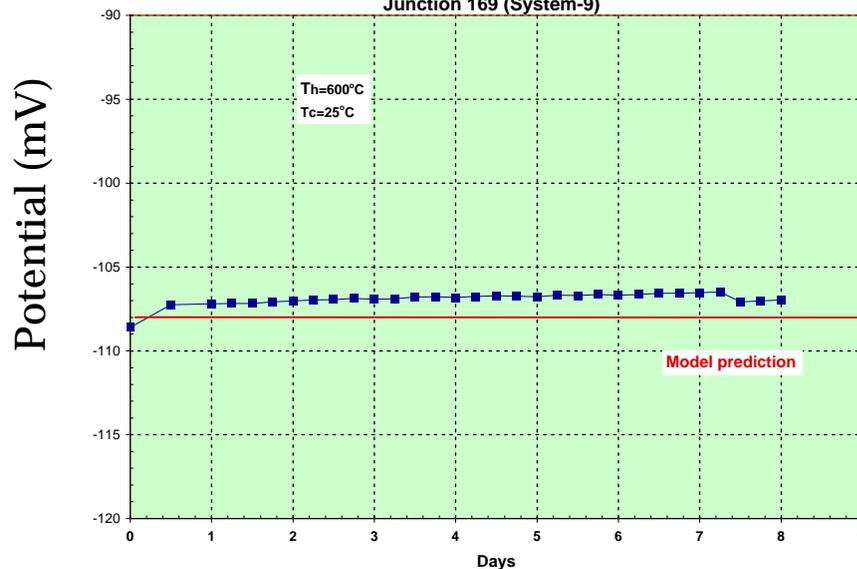
■ Demonstrated low electrical resistance contacts between  $\text{Bi}_2\text{Te}_{2.85}\text{Se}_{0.15}$  and  $\text{CoSb}_3$  segments

# In gradient voltage output and resistance measurements for $\text{Bi}_2\text{Te}_{2.85}\text{Se}_{0.15}/\text{CoSb}_3$ segmented leg (n-type)

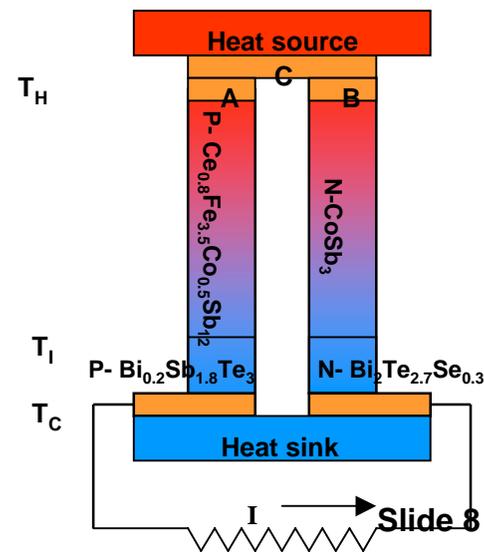
Junction 169 (System-9)



Junction 169 (System-9)

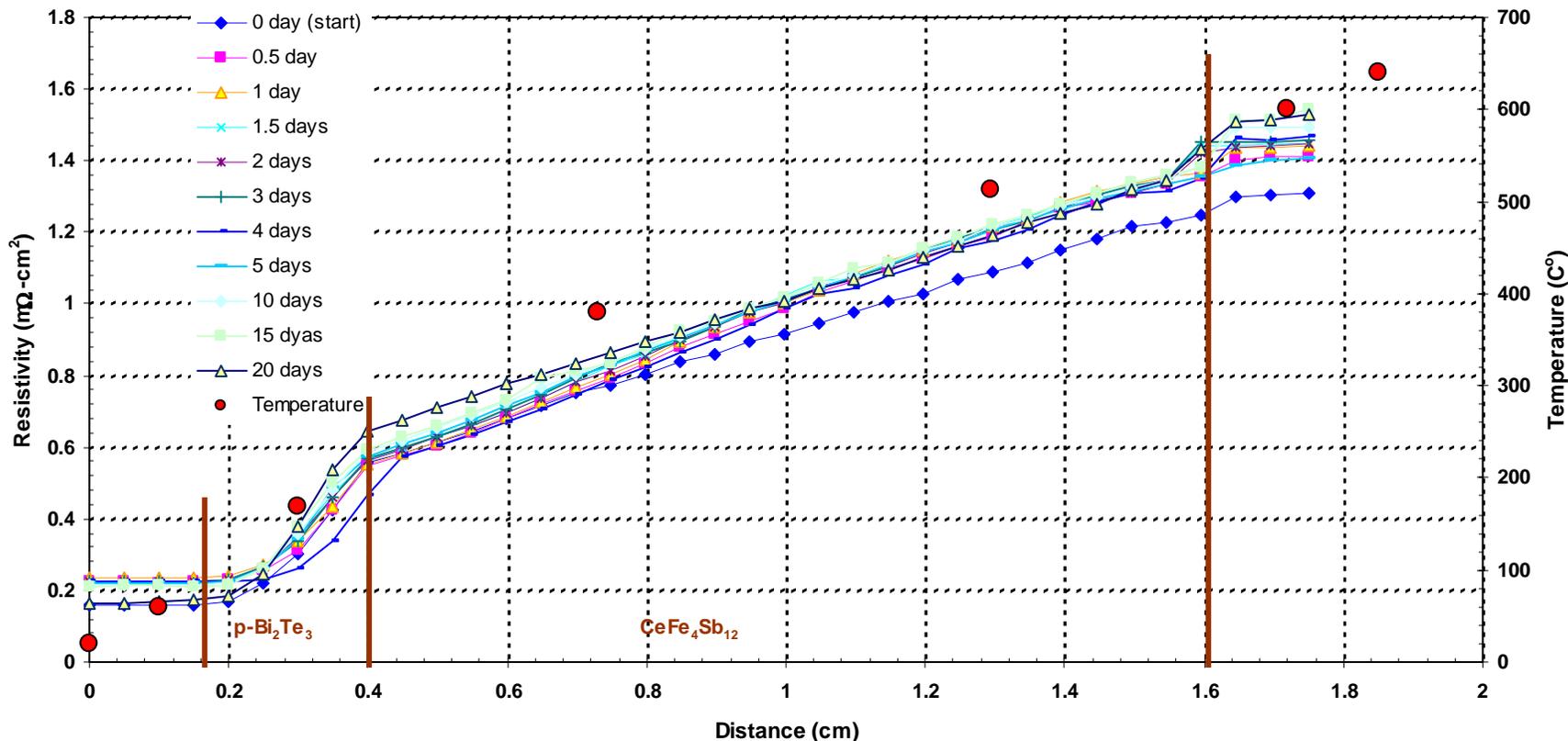


- Results validate thermoelectric properties of n-type  $\text{CoSb}_3$   $\text{Bi}_2\text{Te}_{2.85}\text{Se}_{0.15}\text{CoSb}_3$  segmented leg
- Confirms low electrical contact resistance between segments



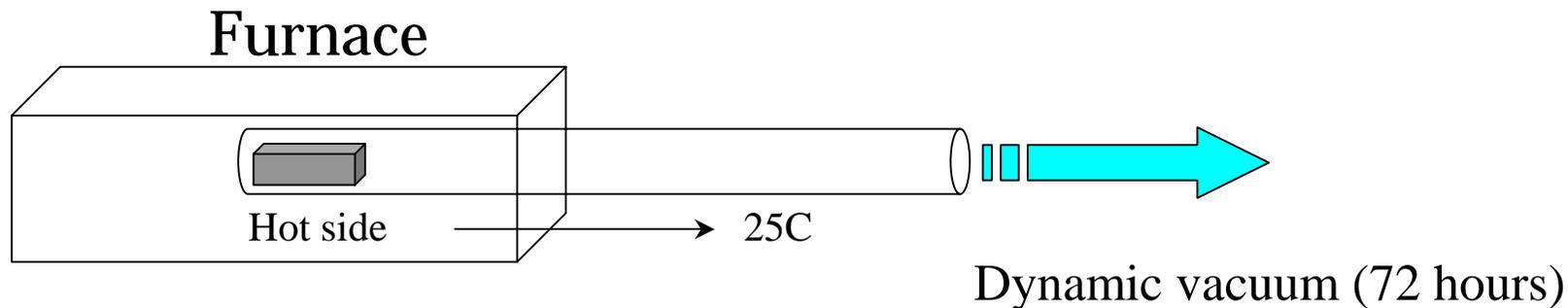
# In gradient electrical contact resistance life tests on $\text{Bi}_{0.4}\text{Sb}_{1.6}\text{Te}_3/\text{CeFe}_4\text{Sb}_{12}$ segmented leg (p-type)

Junction DGF-98 at 600°C

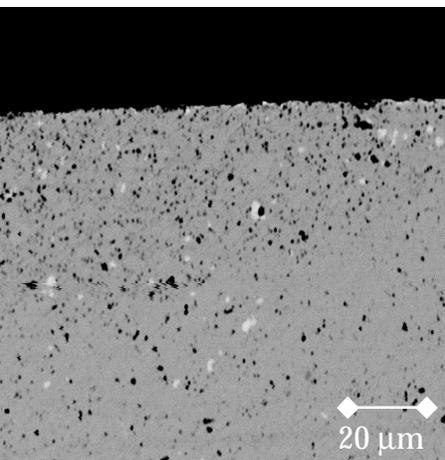


- Demonstrated low electrical resistance contacts between  $\text{Bi}_{0.4}\text{Sb}_{1.6}\text{Te}_3$  and  $\text{CeFe}_4\text{Sb}_{12}$  segments

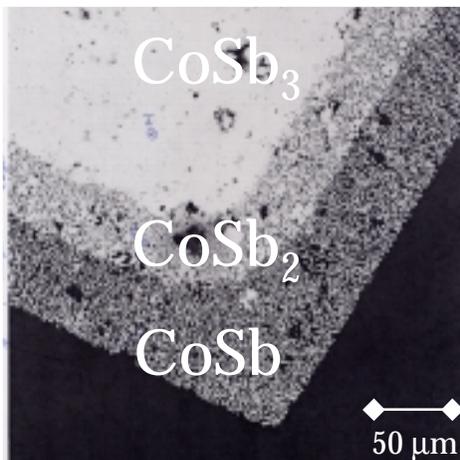
## *n-type temperature stability*



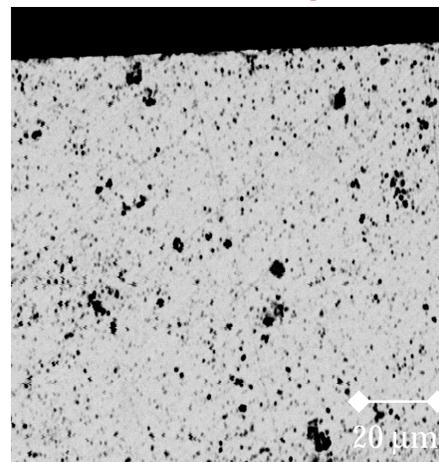
As-pressed



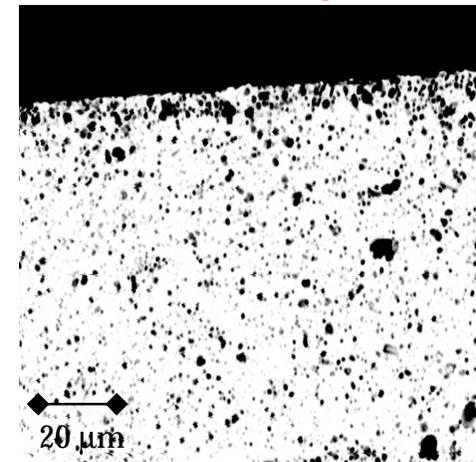
600 dynamic



600 cover gas

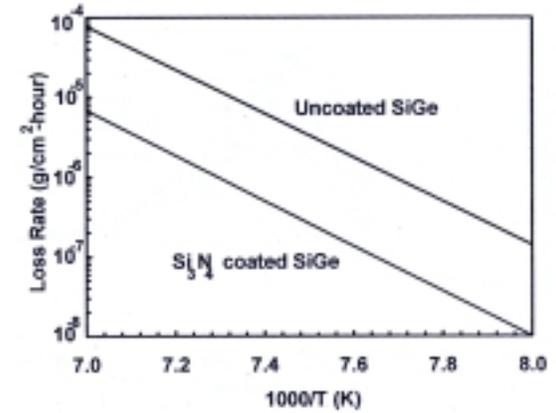
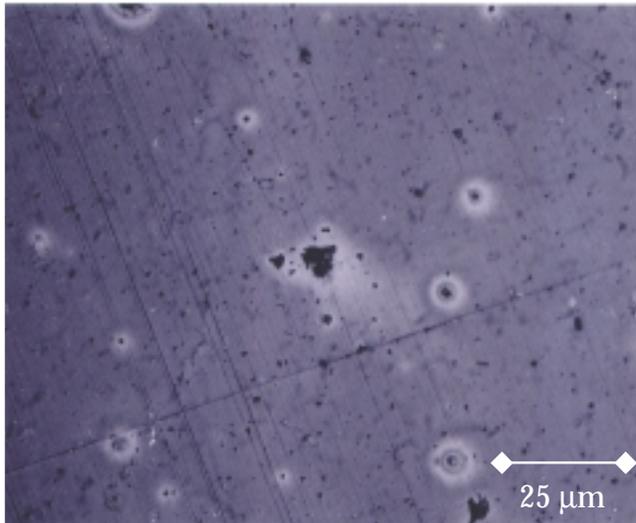
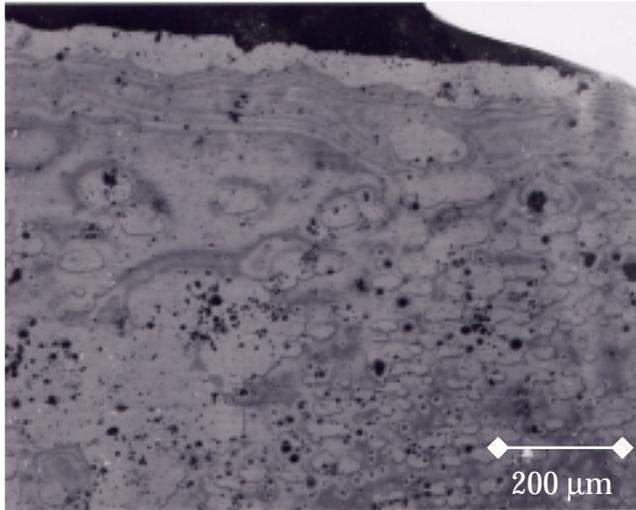


700 cover gas



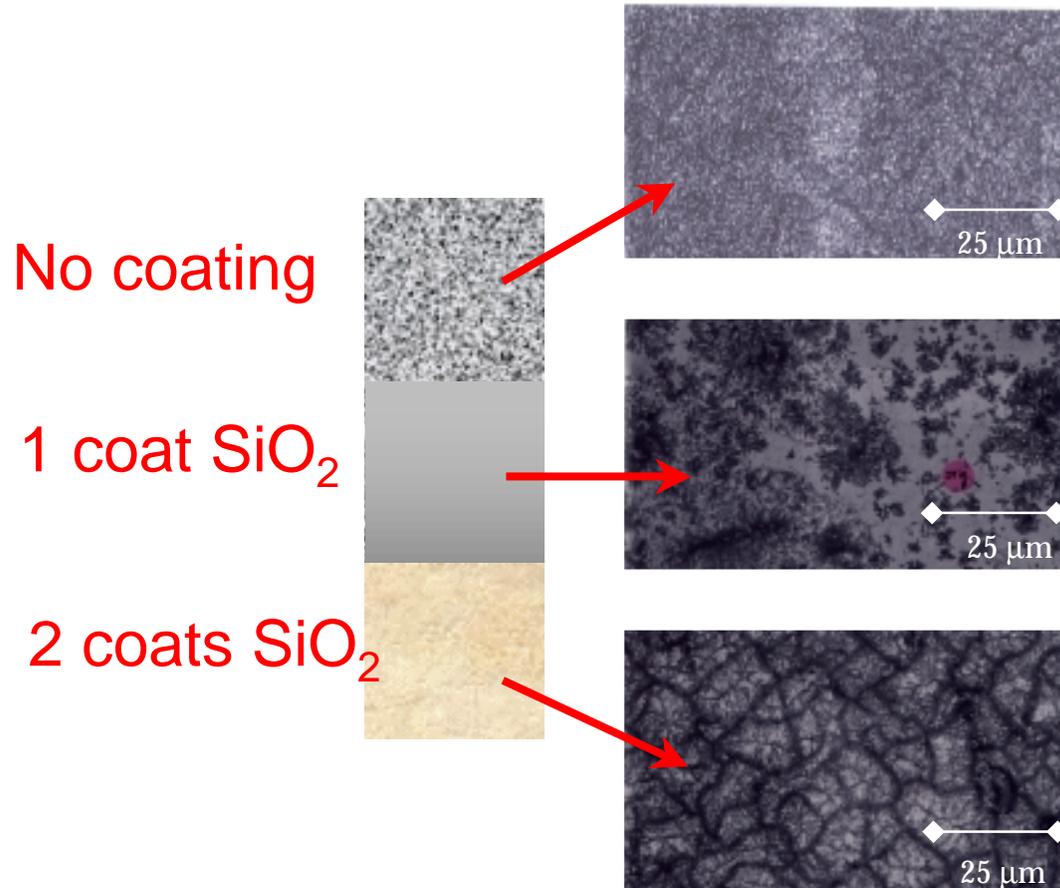
- Temperature stability tests have identified Sb sublimation as the predominant material dissociation mechanism in dynamic vacuum
- Cover gas suppresses Sb sublimation

# Sol-gel silica coatings

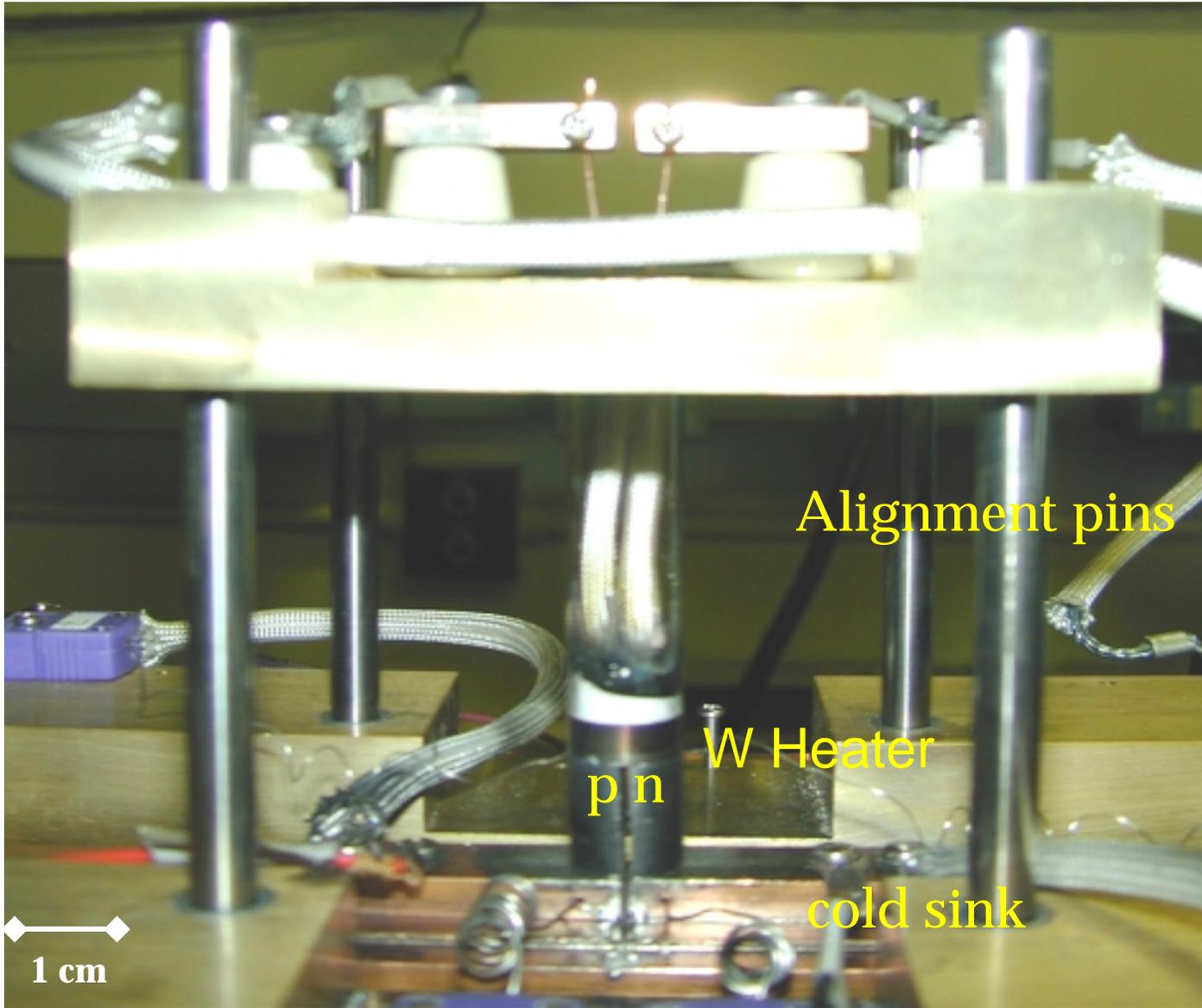


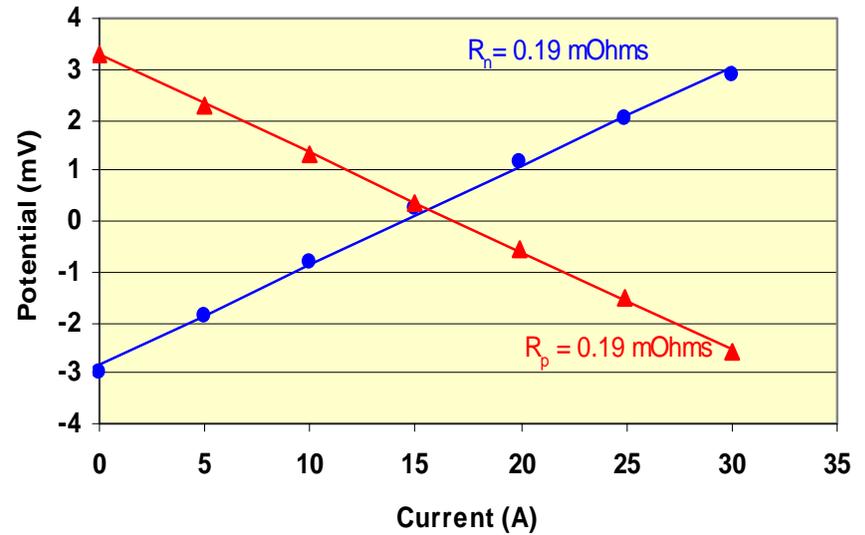
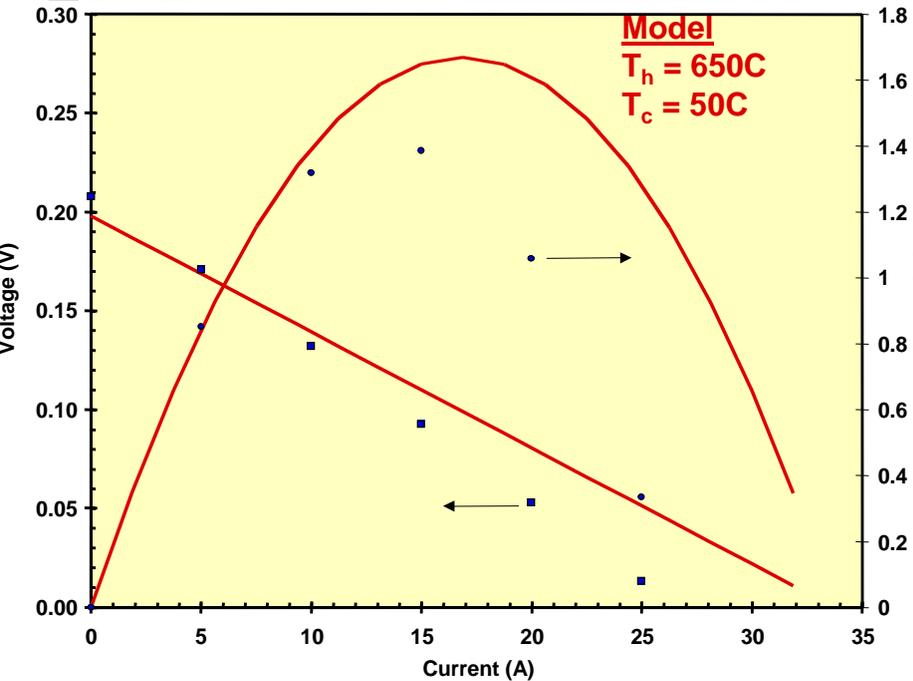
- To prevent sublimation in vacuum; use coating similar to SiGe technology
- Sol-gel; dip coating SiO<sub>2</sub> method
- 1 coat: <500 nm
- Non-conductive and thermally insulating
- Stable < 900°C
- Improve coating quality by minimizing TE porosity

## Sol-gel coatings suppress Sb sublimation



- Sample heated to 600C/dynamic vacuum/72 hours
- Single coat provides good protection





Contact resistance

- **Primary objective: demonstrate 15% efficiency to match predicted performance**
  - **Consistently achieve > 10% efficiency**
  - **Hot-side, contact resistance must be reduced**
    - **Achieved by optimizing braze material and method of brazing**

## Thermal to Electric Power Generation

- Integration with any heat source
  - ◆ Combustors
  - ◆ Catalytic reactors
  - ◆ Radioisotope heat source

## Waste heat recovery

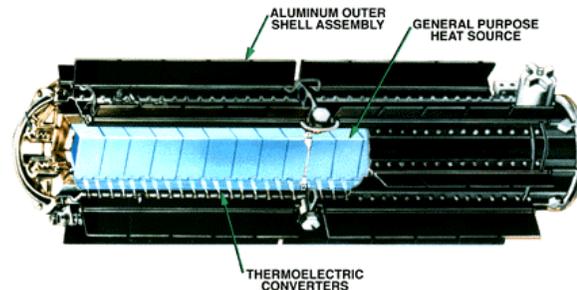
- Automobile exhaust
  - ◆ Supplement or replace electrical power generator with electrical power generated from engine waste heat
  - ◆ T ~ 600 to 700C available at the catalytic converter
  - ◆ ~1 kW power generator
  - ◆ Cost is critical

- Power plants
- Geothermal energy
- Jet engines

## Solid State Advantage

- No moving parts
- No maintenance
- Long life

### General Purpose Heat Source (GPHS) Radioisotope Thermoelectric Generator (RTG)



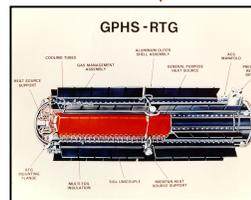
- POWER OUTPUT – 285 W(e)
- FUEL LOADING – 4400 W(t); 132,500 Ci
- WEIGHT – 124 lbs
- SIZE – 16.6 in x 44.5 in

The three Radioisotope Thermoelectric Generators (RTGs) provide electrical power for Cassini's instruments and computers. They are being provided by the U.S. Department of Energy.

### Advanced TE Segmented Unicouples



Advanced Power Generation TE Modules



Radioisotope Thermoelectric Generators



Waste heat Automobile



- **New segmented thermoelectric unicouples under development**
  - Operating between 300 and ~ 1000K
  - Predicted efficiency up to 15 %
- **Unicouple fabrication and testing**
  - Several segmented and non-segmented unicouples built for thermal and electrical testing
  - 10% thermal to electrical efficiency routinely demonstrated
  - Several engineering and processing challenges remain

## Acknowledgement

- **NASA, DARPA and ONR**